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VARIATIONS OF THE RELATIVE ABUNDANCES OF HE, (C,N,O) AND FE-GROUP NUCLEI IN SOLAR COSMIC RAYS AND THEIR RELATIONSHIP TO SOLAR PARTICLE ACCELERATION

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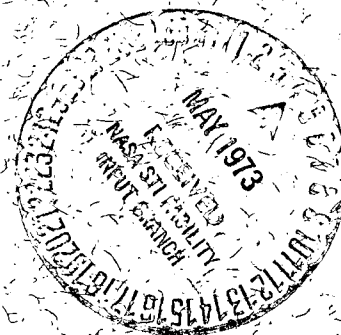
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ABSTRACT

Measurements of the flux of helium nuclei in the 24 January 1971 event and of helium and (C,N,O) nuclei in the 1 September 1971 event are combined with previous measurements to obtain the relative abundances of helium, (C,N,O), and Fe-group nuclei in these events. These data are then summarized together with previously reported results to show that, even when the same detector system using a dE/dx plus range technique is used, differences in the He/(C,N,O) value in the same energy/nucleon interval are observed in solar cosmic ray events. Further, when the He/(C,N,O) value is lower the He/(Fe-group nuclei) value is also systematically lower in these large events. When solar particle acceleration theory is analyzed, it is seen that the results suggest that, for large events, Coulomb energy loss probably does not play a major role in determining solar particle composition at higher energies (> 10 MeV). The variations in multicharged nuclei composition are more likely due to partial ionization during the acceleration phase.

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I. INTRODUCTION

The earliest measurements on the relative abundances of the energetic solar cosmic ray multicharged nuclei of the same charge-to-mass ratio, particularly He, C, and O, showed a remarkable similarity from event to event (e.g., Biswas and Fichtel, 1965 and Bertsch et al. , 1972), especially in view of the dramatic variation in the proton to helium ratio. This latter ratio showed variations of well over an order of magnitude from event to event and with energy in a given event in the range from 10 to 100 MeV/nucleon. The variability of the proton abundance relative to that of He^4 nuclei was not unexpected because, having very different charge-to-mass ratios, they have very different rigidities for the same velocity, and both the acceleration and propagation of solar particles are thought to be velocity and rigidity dependent. On the other hand, the He to (C,N,O) ratio was so similar in the earlier measurements mentioned that over a total of six events no variation was seen above about 15 MeV/nucleon (40 MeV/nucleon in the earlier events) within the accuracy that the ratio could be determined, about 25%. Further, within very limited statistics, the nuclei heavier than oxygen seemed to be present in about the same abundance each time.

Especially within the last two years, however, a number of observations have been made supporting a variability of the relative abundances of these heavier nuclei, although the variability is apparently small compared to that of the proton to helium ratio. Armstrong et al. (1972) summarized the He/(C,N,O) data available

and showed that the values measured recently at low energies ($\lesssim 5$ MeV/nucleon) were clearly different from those which had been determined at the higher energies. Teegarden et al. (1973) later measured a He/(C,N,O) value of 26 ± 2 at 8.5 to 23 MeV/nucleon similar to those at the lower energies rather than the values about twice as large measured previously at higher energies. At the same time, Mogro-Campero and Simpson (1972), Teegarden et al. (1973) and Bertsch et al. (1972) began to notice possible differences in other heavy nuclei abundances, such as Mg, Si, and Fe. Crawford et al. (1972) also measured a small variation of Fe/Si with energy in a single event. This latter variability was not entirely unexpected, however, due to the somewhat different charge-to-mass ratio of Fe, namely .46 rather than 0.50 for Si, O, N, C, and He.

There is clearly a desire to have a better understanding of the situation with regard to heavy nuclei. In addition, there remained the concern that, although it seemed the experiments had all been carefully performed, it might be that part of the variability was due to differences in the experimental techniques and possible undetected errors in one or more of the experiments. The nuclear emulsion sounding rocket program SPICE (Solar Particle Intensity and Composition Experiment) which has provided much of the higher energy data and also was an outgrowth of the earlier program which discovered heavy nuclei in the solar cosmic rays, has obtained exposures in the large solar particle events of January and September 1971. The results of the data analysis of these exposures provide an example of a significantly different He

to (C,N,O) ratio in the same energy/nucleon range in two different
events using the same experimental techniques as well as correlated
variations in the He to Fe-group nuclei ratio. (Fe-group is defined
to be the charge interval $22 \leq Z \leq 28$, but expected to be predominantly
iron; for simplicity this group will be referred to as iron for the
remainder of the paper.) This work will be reported here and discussed
along with related results from the same experimental series. These
data will then be summarized along with others and the problem of
solar particle acceleration will be analyzed particularly from the
point of view of bias in the heavy nuclei composition.

II. EXPERIMENTAL TECHNIQUE

Charge identification and energy measurements of solar cosmic
ray particles are made by analyzing tracks in nuclear emulsions exposed
above the atmosphere during solar particle events. NIKE-APACHE
sounding rockets are used to launch the SPICE payloads which are kept
on standby at the Fort Churchill Research Range at Fort Churchill,
Manitoba. During flight, the nosecone of the SPICE payload is open
for a period of 245 sec. above an altitude of 60 km exposing two
emulsion stacks of dimensions 6.4 cm x 7.1 cm, each protected by a
thin, 27 mg/cm^2 stainless-steel cover. The payload is spin-stabilized
to maintain the emulsion surfaces in a vertical plane. The useful
exposure factor for particles entering the emulsion from the upper
hemisphere is 1.5 m^2sr. sec. per stack. Measurements reported here
were obtained in flights 0819 and 1512 UT on 25 January 1971 and at
0758 on 2 September 1971.

The two stacks were composed of Ilford K.5 and K.2 emulsion respectively. The outer pellicle of each stack was 200 microns thick followed by three 300-micron and approximately twenty 600-micron pellicles, the thinner plates being included to accomodate the high density of low-energy proton tracks in the outer pellicles.

To obtain fluxes of helium nuclei a portion of the area of an emulsion plate from the K.2 stacks was scanned for tracks of all particles whose direction of arrival was above the earth's horizon and whose dip angles are between 10 and 60 degrees from the emulsion surface. A minimum length projected in the emulsion plane of typically 130 microns was required for each track in order to assure an adequate track length for charge identification. Each track was followed to its endpoint to determine its residual range and grain counts were made near the entrance point in the scan emulsion. Plots of grain density as a function of range were used to resolve the helium nuclei from protons. (With this method approximately 50 protons must be measured for each helium nucleus.) Details on this technique and the resolution of helium that is obtainable with this method have been reported previously (Bertsch et al., 1972). Independent scans were made at different depths in each stack to provide improved information in the energy region between 10 and 50 MeV/nucleon where the (C,N,O) nuclei spectra have been measured (Bertsch et al., 1973).

III. RESULTS

Measurements of the composition of solar cosmic rays in the region of nuclei ranging from helium to iron have been made in several

solar particle events since September 1966. In this section, the flux

of helium during the 1 January 1971 event and the fluxes of helium and

(C,N,O) during the 1 September 1971 event are reported. These results

together with earlier published data from the SPICE series are used

to form abundance ratios for helium, (C,N,O), and Fe nuclei in four

different solar particle events. For three of the events, iron is

compared directly with helium and (C,N,O) nuclei in overlapping energy

regions and in the fourth event where no iron was detected, limits to

ratios involving iron are given.

It will be seen that statistically significant differences in the

He/(C,N,O), He/Fe, and (C,N,O)/Fe abundance ratios exist for different

particle events indicating that solar cosmic ray composition is variable

between events. Moreover, the results indicate that the variations

are a systematic function of the particle charge. Evidence of solar

cosmic ray composition variability from other workers is summarized

at the end of the section.

Table I shows the flux measurements of helium nuclei at two

different times during the 24 January 1971 particle event associated

with a flare at 2309 UT. Also given in Table I are the helium and

(C,N,O) fluxes in the 1 September 1971 event at approximately 12 hours

after the flare.

Using these data and previously published results on helium,

(C,N,O),and iron fluxes (Durgaprasad et al., 1968; Bertsch et al.,

1972 and 1973), abundance ratios of helium to (C,N,O),helium to iron,

and (C,N,O) to iron have been determined for all solar particle

events studied during the current SPICE series and these are

TABLE I. DIFFERENTIAL HELIUM AND (C,N,O) NUCLEI IN SOLAR PARTICLE EVENTS DURING 1971.

Flight	Helium Nuclei		(C,N,O) Nuclei	
	E MeV/N	$\frac{dJ}{dE}(cm^2-sr-sec-MeV/N)^{-1}$	E MeV/N	$\frac{dJ}{dE}(cm^2-sr-sec-MeV/N)^{-1}$
25 Jan 1971 0819 UT	20	0.41 ± 0.14	Reported previously. See Bertsch et al. (1973)	
	26	0.38 ± 0.14		
	33	0.29 ± 0.10		
25 Jan 1971 1512 UT	17.8	0.97 ± 0.24		
	22.5	0.47 ± 0.15		
	27.5	0.08 ± 0.08		
2 Sept. 1971 0758 UT	17	0.30 ± 0.10	13.2	0.0357 ± 0.0042
	25	0.11 ± 0.03	15.8	0.0254 ± 0.0029
	36	0.041 ± 0.015	18.4	0.0145 ± 0.0023
			22.1	0.0073 ± 0.0011
			26.2	0.0033 ± 0.0006
			30.3	0.0024 ± 0.0004
			34.1	0.0016 ± 0.0004
			39.7	0.0007 ± 0.0002
			47.0	0.0003 ± 0.0001

summarized in Table II. In the case of the 12 April 1969 event, no iron nuclei were detected and only lower limits (at a 95% confidence level) could be determined. Helium and iron were not observed in significantly overlapping energy regions in the second flight in January 1971. However Crawford et al. (1972) measured heavy nuclei in plastic detectors flown aboard the same payload, and the energy spectrum for the iron nuclei which they observe agrees quantitatively with the iron spectrum measured in emulsions (Bertsch et al., 1973). For this reason, the iron data of Crawford et al. (1972) were combined with the iron data from the emulsions in order to estimate the helium to iron ratio shown in parenthesis in Table II.

Notice that the ratios (or lower limits) for the September 1966 and April 1969 events are significantly higher than the three measurements in the two 1971 events. In particular, the helium to (C,N,O) ratios for January and September 1971 are approximately a factor of two lower than the weighted average of 58±5 for nine earlier measurements above 10 MeV/nucleon (including September 1966 and April 1969) summarized by Bertsch et al. (1969) and Armstrong et al. (1972).

Furthermore, the ratios in Table II show that when (C,N,O) nuclei are enhanced relative to helium that iron is enhanced relative to helium and apparently to (C,N,O) nuclei as well which implies a systematic enrichment of heavy nuclei relative to light nuclei, or alternately that light nuclei are suppressed with respect to heavy nuclei. If these data are analyzed in smaller energy intervals there

TABLE II. SUMMARY OF ABUNDANCE RATIOS IN SOLAR PARTICLE EVENTS

Event	Time (Hr)	Helium-to-(C,N,O)		Helium-to-Iron		(C,N,O)-to-Iron		Ref.
		Ratio	Energy(MeV/N)	Ratio	Energy(MEV/N)	Ratio	Energy(MeV/N)	
2 Sept 1966	1443 UT	48±8	12 to 35	2540±540	21 to 38	57±18	21 to 40	a,b
12 Apr 1969	2319 UT	55±8	18 to 34	> 1900*	21 to 34	> 35*	21 to 50	c,b
25 Jan 1971	0819 UT	29±7	17 to 46	1070±280	21 to 50	28±6	21 to 50	d,b
25 Jan 1971	1512 UT	27±6	16 to 30	(810±270)	15 to 30	29±7	21 to 50	d,e,b
2 Sept 1971	0758 UT	22±4	14 to 42	810±290	21 to 42	30±9	21 to 50	d,c

*Based on 95% confidence limits

References: (a) Durgaprasad et al., 1968 (b) Bertsch et al., 1973,
            (c) Bertsch et al., 1972, (d) This paper, (e) Crawford et al., 1972.

is a tendency for the ratios in the January and September 1971 events
to increase as a function of energy. Based on the helium to (C,N,O)
ratios surveyed earlier (Bertsch et al., 1972) and the ratios given in
Table II for the January 1971 event, no significant variation of
relative abundances with time in an event is observed.

Evidence for variability of solar cosmic ray composition between
flare events from the work of other groups will now be summarized. With
regard to the relative abundances of He and (C,N,O) nuclei, Armstrong
and Krimigis (1971) summarize the He/(C,N,O) ratio for 35 events during
1967 and 1968 in the energy region of 0.5 to 2.5 MeV/nucleon and conclude
that significant variations exist. Armstrong et al. (1972) compare
these satellite data for He/(C,N,O) which have an average value of 27±9 with
the SPICE emulsion results from 1960 to 1969 which average to 58±5 for
energies of 12 to 100 MeV/nucleon. The comparison of results suggest
the possibility of energy and event-to-event time variations. Teegarden
et al. (1973) report He/O ratios which differ significantly between the
April 1971 and September 1971 events. In the latter case they obtain
a He/(C,N,O) value of 26±2 which agrees with the SPICE result for that
event given in Table II. Teegarden et al. (1973) observe Fe/O ratios
in the April and September 1971 events that differ by a factor of six,
but are statistically consistent with a constant value. Generally,
they conclude that the composition in these two events is similar to
the solar photospheric estimates as are the earlier results of Biswas
et al. (1962) and Bertsch et al. (1972). Mogro-Campero and Simpson (1972),

on the other hand, derive Fe/O values above 5 MeV/nucleon for seven

particle events that show significant variability by as much as a

factor of 20. Their results are obtained by integrating over a major

portion of an event, and by extrapolating the oxygen spectrum from

14 down to 5 MeV/nucleon using the spectral data from another satellite.

Overall averages of all seven events imply that solar cosmic rays above

Si are preferentially enhanced (10 to 20 times for iron) relative to

solar photospheric values.

Crawford et al. (1972) using plastic detectors flown aboard SPICE

sounding rockets find no evidence of composition variations between

the January and September 1971 events, but do observe that the Fe/Si

ratio decreases with energy by a factor ≈ 4 over the energy range from

1.5 to 40 MeV/nucleon. It is important to note that the charge-to-mass

ratios Fe and Si differ by $\approx 8\%$ at energies where the nuclei are fully

stripped of electrons (≈ 25 MeV/nucleon) and at lower energies where

the nuclei may be only partially ionized even larger differences in

the charge-to-mass ratio are possible so that variations in ratios from

propagation and acceleration processes might be expected.

Based on analyses of a piece of Surveyor 3 camera filter exposed for

2.6 years on the moon, Price et al. (1971) compare the iron spectrum to

a helium spectrum obtained from satellite data integrated over the same

time interval in the energy region of 6-10 MeV/nucleon. He/Fe inferred

from their results range from ≈ 230 at 6 MeV/nucleon to ≈ 560 at 10 MeV/

nucleon. The value at the higher energy does not differ appreciably

from values in Table II, particularly in view of the difficulty in

comparing different experimental results on steep spectral distributions.

IV. DISCUSSION

As indicated in the previous section, the measurements now

existing on the He to (C,N,O) ratio show clearly that there is a varia-

tion in this ratio from one solar particle event to another. Further,

the data as a whole also suggest a variation in the ratio with energy.

It was also seen that the evidence supports the concept that when the

(C,N,O) nuclei are higher in abundance relative to He nuclei, the Fe

nuclei are not only higher in abundance relative to He nuclei, but

apparently to (C,N,O) nuclei also.

There are three possible explanations for this variation. These

are: (1) variations in source region composition, (2) bias intro-

duced during the acceleration phase (including injection), and (3) bias

introduced during the propagation phase. The latter will be discussed

first.

From a theoretical point of view, there should be no differences

in propagation for nuclear species that have the same charge-to-mass

ratio since they have the same magnetic rigidity for a given velocity,

and it is only these two parameters of the particle which enter the

propagation equations. That is, no matter how complex the magnetic

field configuration in space and time, two particles starting at the

same place and time and going in the same direction will follow the

same trajectory, if their velocity and rigidity are the same. Although

their velocity may change due to adiabatic deceleration, they will

change by the same amount, since this deceleration is basically

electromagnetic in nature. However, it is worth noting that, if a

variation of some abundance ratio with energy/nucleon already existed,

the value at high energies would be shifted to lower energies; so a

change in that abundance ratio might be seen in a given energy/nucleon

interval at the detector. This effect, however, to emphasize the point,

occurs only if a variation of the ratio with energy/nucleon already

exists.

The C, N, O, and He nuclei will have the same rigidity for a given

velocity, of course, only if they are fully ionized. In the energy/

nucleon region with which we are primarily concerned here, namely

> 10 MeV/nucleon, they are almost certainly fully ionized because the

equilibrium effective charge is the fully ionized charge. Thus, all

these considerations speak against propagation alone introducing any

bias. In addition, there are many data (Biswas et al., 1962; Biswas,

et al., 1963; Durgaprasad et al., 1968; Teegarden et al., 1973; this

work) to show that the ratio usually appears to remain constant during

an event within uncertainties, which are small compared to the

differences in He/(C,N,O) seen between different events.

Both source region variations and acceleration may introduce

relative abundance biases. Indeed when the early solar cosmic ray data

seemed to support a constant composition of the multi-charged nuclei

from one solar particle event to another (e.g. Biswas et al., 1962),

it was realized that a rather stringent set of circumstances would

have to exist if subsequent data did confirm a constant set of relative

abundances. Now that variations in relative abundances among particles with the same nuclear charge-to-mass ratio are observed, it seems to be worth reviewing the possibilities which exist for the solar particle acceleration process to examine wherein the bias can enter. The exact nature of the acceleration process is not known, but only a few fundamental mechanisms seem available.

In any process leading to the acceleration of particles, the rate of energy gain in the acceleration must exceed that of the energy losses which are present. The predominat forms of energy loss for solar particles would be collision losses; however, if the acceleration occurs very rapidly, in approximately 10^2 sec., and in a region of relatively low density, of the order of 10^9 particles/cm^3 or less, the loss rate is negligible, at least above about one MeV/nucleon. For acceleration theories involving long periods of time, (including that during which the particles may be trapped in a local region after acceleration) or regions of high density, the energy losses must be seriously considered, since, in addition to other considerations, different nuclear species lose energy at different rates. The much higher rate of energy loss for heavier nuclei would cause them to be suppressed at high energies possibly causing both a suppression of heavy nuclei and abundance variations between events. For example, if nuclei with an observed energy of 20 MeV/nucleon had passed through 0.2 g/cm^2, Fe would be depressed relative to He by a factor of almost six for an E_N^{-2} spectrum and by a factor of about twelve for an E_N^{-3} spectrum. Oxygen nuclei

would be suppressed by a factor of 4 relative to He for an E_N^{-3} spectrum. This degree of suppression seems not to be observed. At low energies the degree of the suppression depends on the degree of ionization.

If it is assumed that the energy loss as a result of traversing material occurs during acceleration, the bias result is very model dependent, and this point will be returned to briefly later. The results also depend to some degree on the percentage of ionization of the material.

Turning to acceleration mechanisms, it is not known which of the possible acceleration mechanisms is the predominant one. For magnetic fields, and the associated electric fields as the magnetic fields vary in time, there seem to be only two fundamental ones, the Fermi mechanism and the betatron mechanism. In the Fermi (1949, 1954) accelerating mechanism, the acceleration occurs when a charged particle is reflected by a magnetic region initially moving toward the particle. If the full reflection occurs, the energy/nucleon gained is proportional to the total energy/nucleon of the particle. Even if the probability of reflection is a function of particle rigidity also (as it probably is since the reflection would depend to some degree on the particle's radius of curvature), the rate of acceleration will be the same for particles of the same charge-to-mass ratios. Biswas et al. (1962) suggested that this feature, together with rigidity dependent propagation, could explain the similar energy/nucleon spectra of solar

helium and (C,N,O) nuclei, and the quite different spectra of protons

and helium nuclei. If the nuclei of the same charge-to-mass ratio

are not fully ionized, their effective charge-to-mass ratios generally

will be different. Then a biased abundance ratio can occur, and the

degree of bias may vary with energy/nucleon. It is perhaps worth

mentioning that the currently popular acceleration model of annihilation

of magnetic field lines near a neutral sheet can be shown to reduce to

the Fermi mechanism from the standpoint of particle acceleration

(Parker, 1958).

In the betatron acceleration mechanism, there can, in principle,

be sustained acceleration by an increase in magnetic-field strength,

followed by an averaging of the momentum vector among its three

components by scattering, a decrease in the magnetic field with an

accompanying decrease in energy -- which is, however, smaller than the

increase -- and then more scattering which gives rise to a random

distribution of the momentum vector (Alfven, 1959). Here again, a

biased acceleration can occur if the particles are not fully ionized

because the probability of escape from the region is an increasing

function of rigidity.

Since for both of these mechanisms a particle with a smaller

effective charge-to-mass ratio has a smaller probability of achieving

a higher energy, they have a suppressing effect on partially ionized

nuclei. The most simple assumption, but not the only one as will be

noted, is then that, if the heavier nuclei are not always fully ionized

and if there are no complicating effects from Coulomb energy losses,
there is a good chance that their abundance will sometimes be suppressed,
especially at higher energies. In this case, the He/(C,N,O) value would
be expected to be possibly variable from event to event and in general
larger at a higher energy/nucleon, as observed. Also, when He/(C,N,O)
is larger, He/Fe should be larger also, as observed.

However, as Hirshberg (1973) has noted, the situation need not
be so simple. She points out that it is easier to strip one electron
from (C,N,O) nuclei than from helium nuclei; and, therefore, a larger
fraction of the (C,N,O) nuclei could be started into the acceleration
process, and the ratio of helium to (C,N,O) decreased. It would then
be possible for there to be a general trend of the He/(C,N,O) value
as observed, but with the helium nuclei also suffering a general
suppression.

It is also worth noting that the first ionization potential of
Fe is less than two-thirds that of the average of C, N, and O; so Fe
would be even more likely to be favorably injected than C, N, and O if
the effect being discussed is important. Some of the results reported
in other work mentioned earlier, do suggest that Fe is sometimes favorably
accelerated, although in the large events, such as those discussed in
this work, there seems to be no strong Fe enhancement.

The relative importance of the two competing effects mentioned
above depends on the details of the particle acceleration process, for
which no entirely satisfactory model exists. At this time, the initial
ionization states of the various species are not known and the region

in which the particles to be accelerated originate is not certain.
There have been several models developed specifically to explain a
possible heavy nuclei enhancement. Most of these are related to either
the lower first ionization potential of most heavy particles, already
mentioned, or the relatively low rate of ionization loss of heavier
species when they are only singly or doubly ionized which could give
these particles a favorable acceleration rate just after injection.
As an example of calculations taking into account the effect of ionization
loss of partially ionized particles during a Fermi acceleration see
Ramadurai (1973). His analysis predicts an enhancement of heavy nuclei
at low energies which increases with increasing charge of the accelerated
particles. A more complex model has been proposed recently by Cartwright
and Mogro-Campero (1972) who propose a two region solution with full
ionization in the first region and only partial ionization in the second
after electrons have been added to the nucleus during transit from one
region to the other. The heavy nuclei in the second region then have
a higher rigidity for a given velocity and, therefore, could have their
abundance enhanced if the minimum cut-off rigidity for favorable accelera-
tion suggested by Wentzel (1965) for the Fermi mechanism has an appro-
priate value.

SUMMARY

The number of possible models for favorable or unfavorable
acceleration of heavier nuclei can clearly be quite large, especially
if various combinations of the ideas outlined above are considered.
Possibly then, the more striking feature is that, in spite of the

observed variations in composition, most large events, wherein several

nuclear species have been studied by a single detector, have a very

similar composition. The qualification of the same detector being

used is important because this eliminates spatial variations and cross

calibration difficulties. At least for large events, the results

suggest that Coulomb energy loss does not play a major role in

determining the observed composition at high energies (> 10 MeV/nucleon).

The variations in multicharged nuclei composition are more likely due

to partial ionization during the acceleration phase. Moreover, since

the composition does not appear to be biased to a large degree relative

to photospheric values, heavy particles probably are highly ionized

at the time of acceleration in these very large events.

Differences in composition from event to event among the multiply

charged nuclear abundances even with those of the same charge-to-mass

ratio now clearly do exist, however. Further, the results reported

here which were obtained with the same detector system using a $\frac{dE}{dx}$

vs. range technique, provide, we believe, the first evidence for a

systematic variation of He, (C,N,O), and Fe abundances between different

large events. In particular, the data summarized here show that for

events where the He/(C,N,O) value is low, He/Fe is also low and most

likely to a more pronounced degree. Additional research which is

aimed at the study of the abundance of several multicharged nuclei

in many different events, especially those which differ markedly in

size, or in some other fundamental way, should assist in determining

the nature of the variations and hence give very important clues to
the acceleration process, since, as has been noted, different hypotheses
can lead to different types of biases even differing between enhance-
ment and suppression for certain species.

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